2nd Feasibility Study of a Muon Storage Ring Neutrino Factory

US Muon Collaboration

Oxford 11/2001

R. B. Palmer (BNL)

Today	**14.15**	**US studies of Neutrino Factory** **Study 1, Study 2**
Wed.	**12.00**	**Other studies,** **Experimental Programs, inc. MICE**
Thur.	**12.00**	**Other Ideas:** **CERN & KEK Schemes** **longitudinal cooling, bunched phase rotation,** **FFAG's, Colliders, Radioactive beam neutrinos**
Fri.	**16.15**	**The big picture:** **hadron, electron, muon colliders, neutrino factories**

Feasibility Study 1

- Commissioned by FNAL Director
- FNAL Site specific (where relevant)
- FNAL + Collaboration
- Ed. Finley, Holtkamp (April 2000)

- Emphasize Feasibility
- allow "Entry Level" Performance

Feasible, but less performance

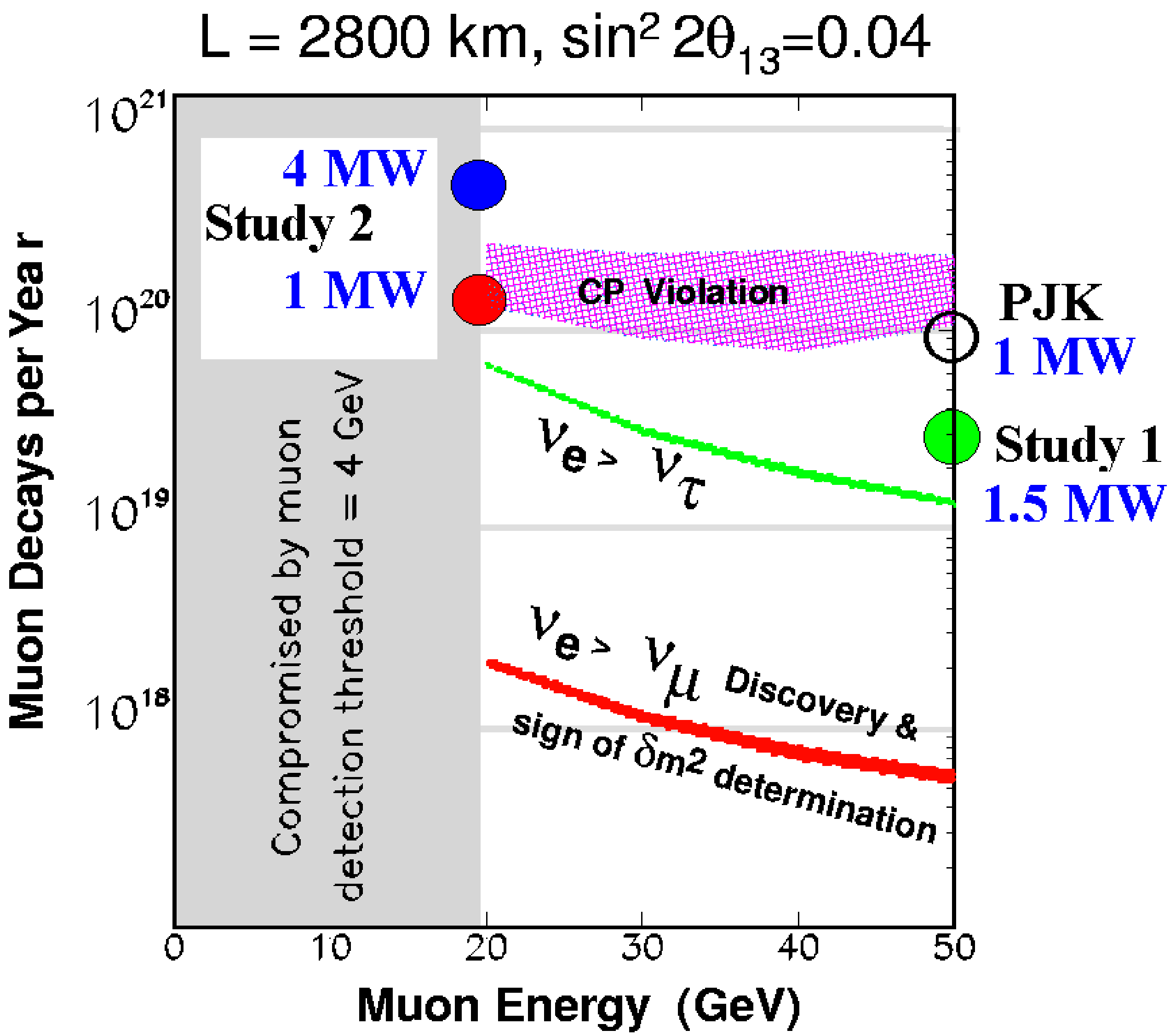
Feasibility Study 2

- Commissioned by BNL Director
- BNL Site specific (where relevant)
- BNL + Collaboration
- Edd. Ozaki, Palmer, Zisman
- Closeout May 4 2001

- Build on Study 1
- Maintain Feasibility
- Raise Performance

Feasible, and 6 $\times$ μ/p

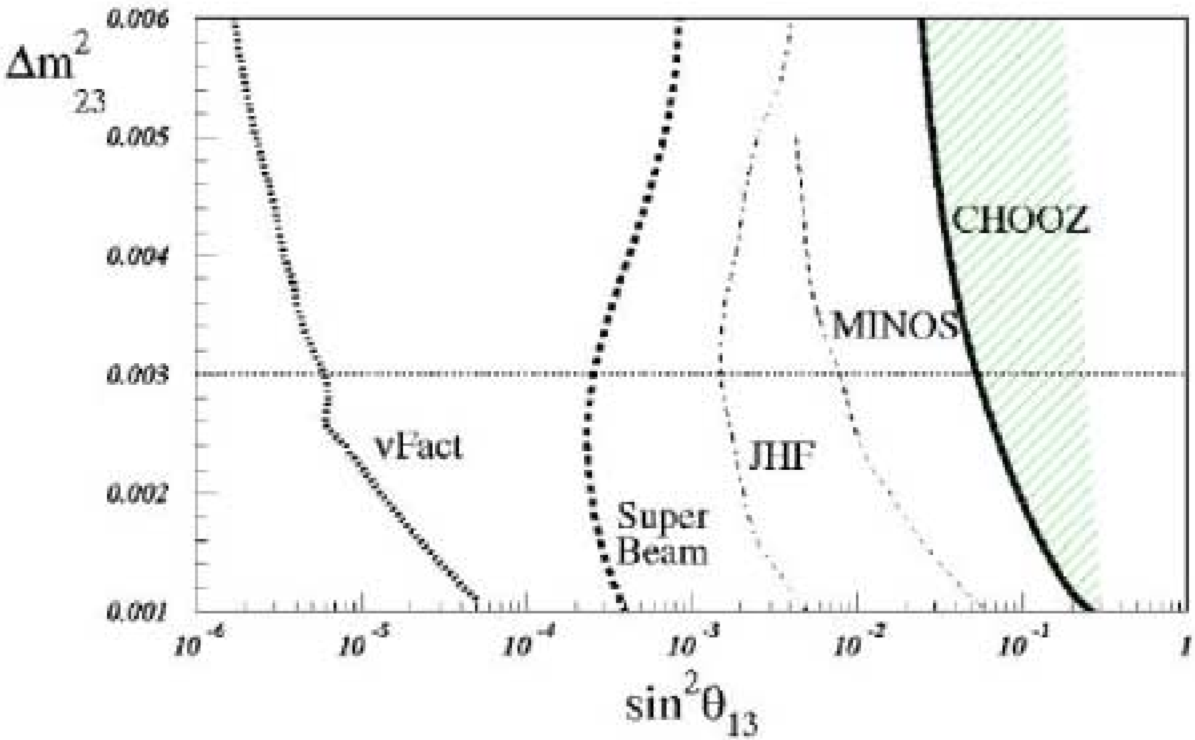
Physics Reach



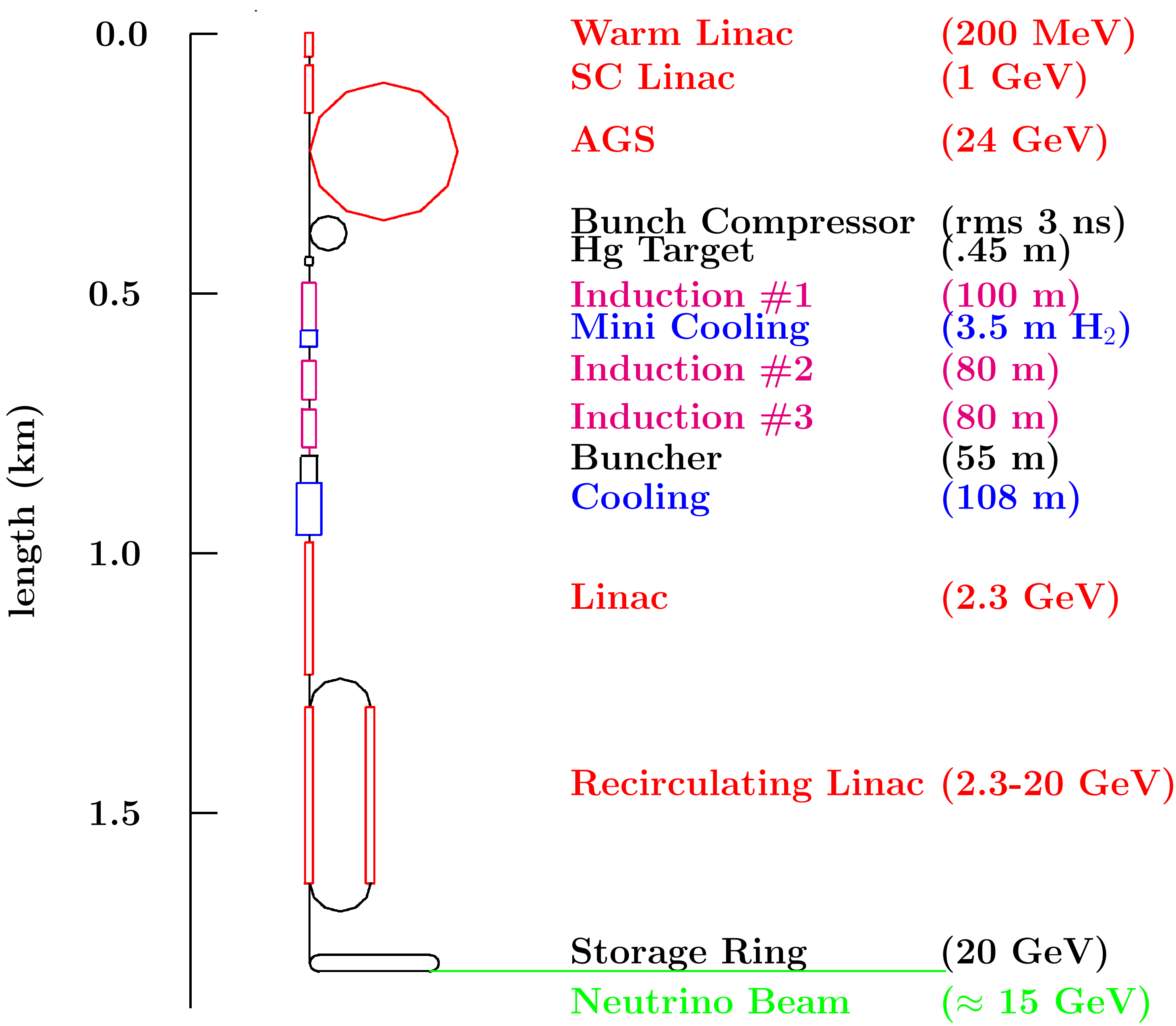
- muon decays in straight section / $1\ 10^7$ sec
- For Detector mass 50 kT
- Best distance: 2000 - 3000 km

WIPP=2900 km Homestake=2500 km

Comparisons



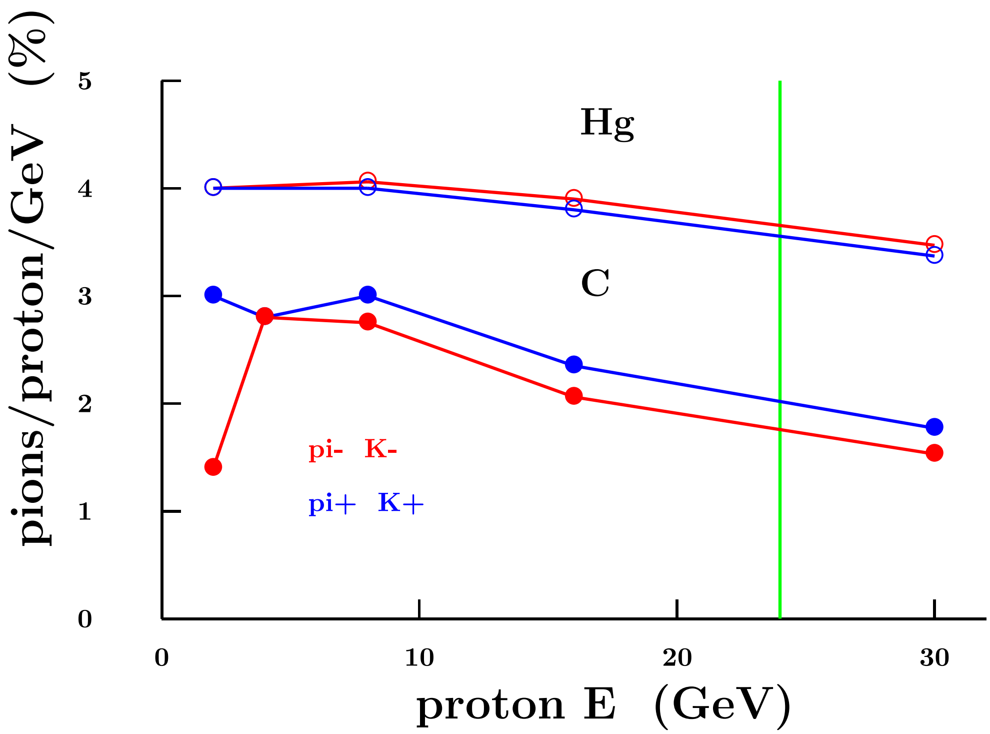
Schematic



length (km)
0.0
0.5
1.0
1.5
Warm Linac (200 MeV)
SC Linac (1 GeV)
AGS (24 GeV)
Bunch Compressor (rms 3 ns)
Hg Target (.45 m)
Induction #1 (100 m)
Mini Cooling (3.5 m H_2)
Induction #2 (80 m)
Induction #3 (80 m)
Buncher (55 m)
Cooling (108 m)
Linac (2.3 GeV)
Recirculating Linac (2.3-20 GeV)
Storage Ring (20 GeV)
Neutrino Beam ($\approx$ 15 GeV)

PION PRODUCTION

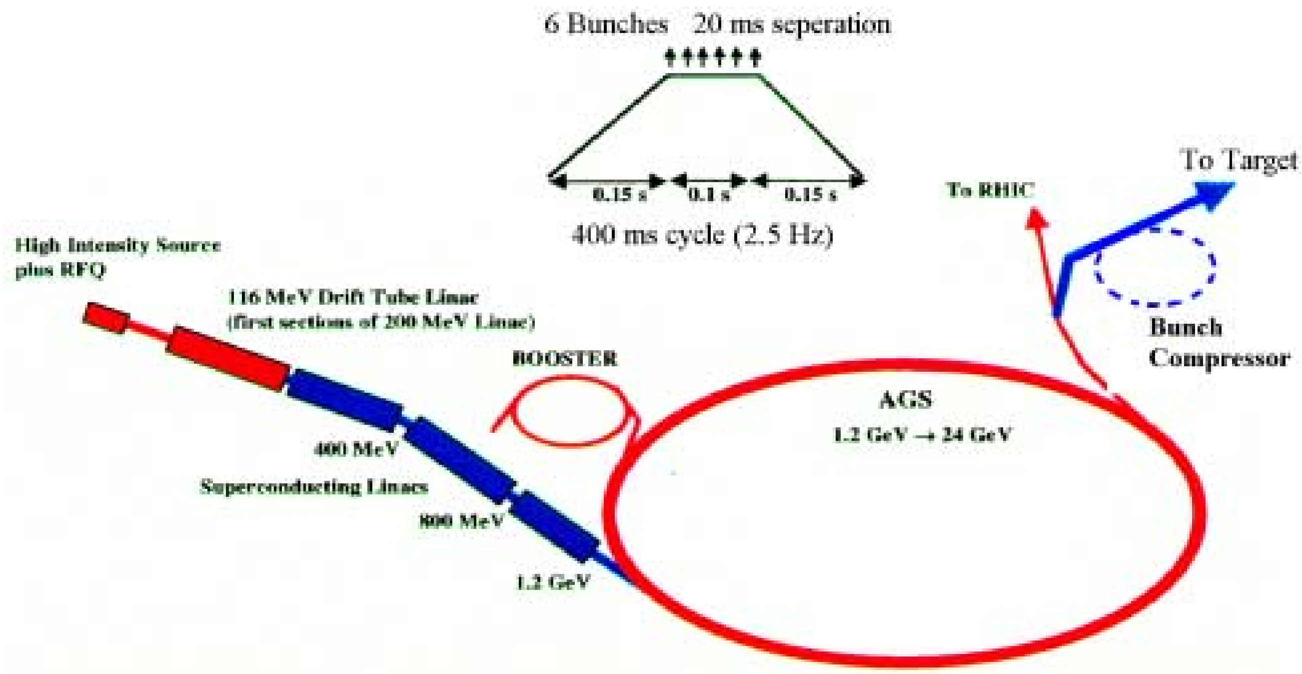
For 50 - 800 GeV/c, pions/proton divided by proton energy in GeV:



- **Hg** $\approx$ **2** $\times$ **C**
- **Low energy slightly better than high**
- **But harder to get short p bunch**

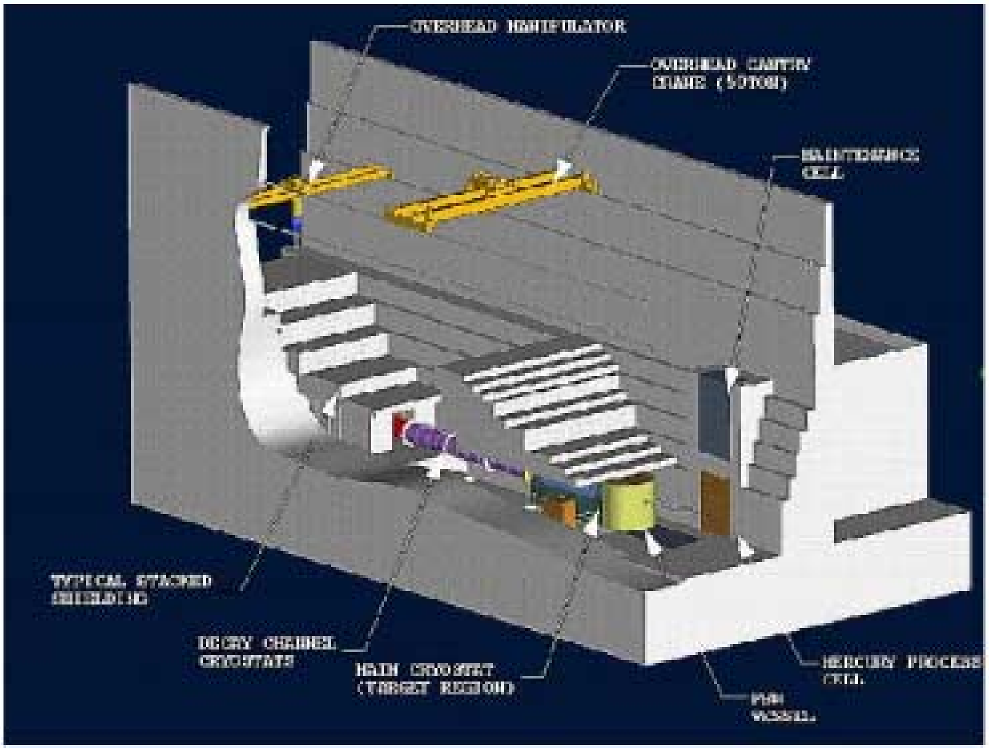
PROTON DRIVER

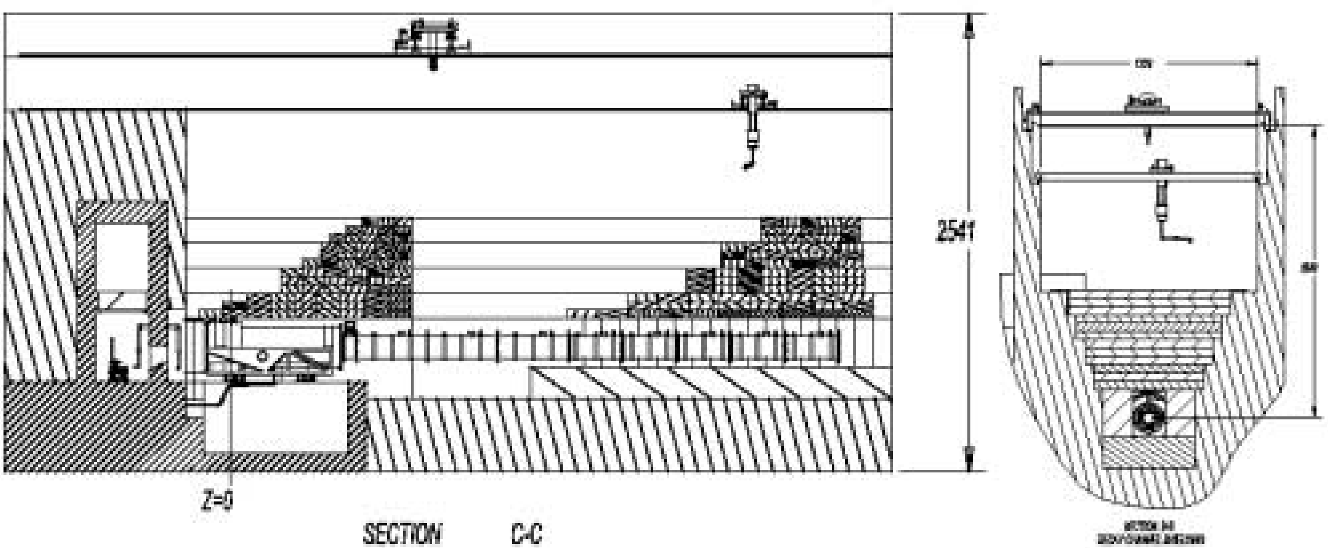
- 1 MW BNL AGS Upgrade
  - New (SNS like) SC Linac
  - Upgraded AGS (.5 $\rightarrow$ 2.5 Hz)
  - 6 single bunch extractions



- 4 MW further upgrade
  - Increases linac E $\rightarrow$ 2 $\times$ charge
  - Accumulator Ring $\rightarrow$ 5 Hz
  - Bunch Compressor
- Similar performance with new 16 GeV Booster at FNAL

Target Area for 4 MW

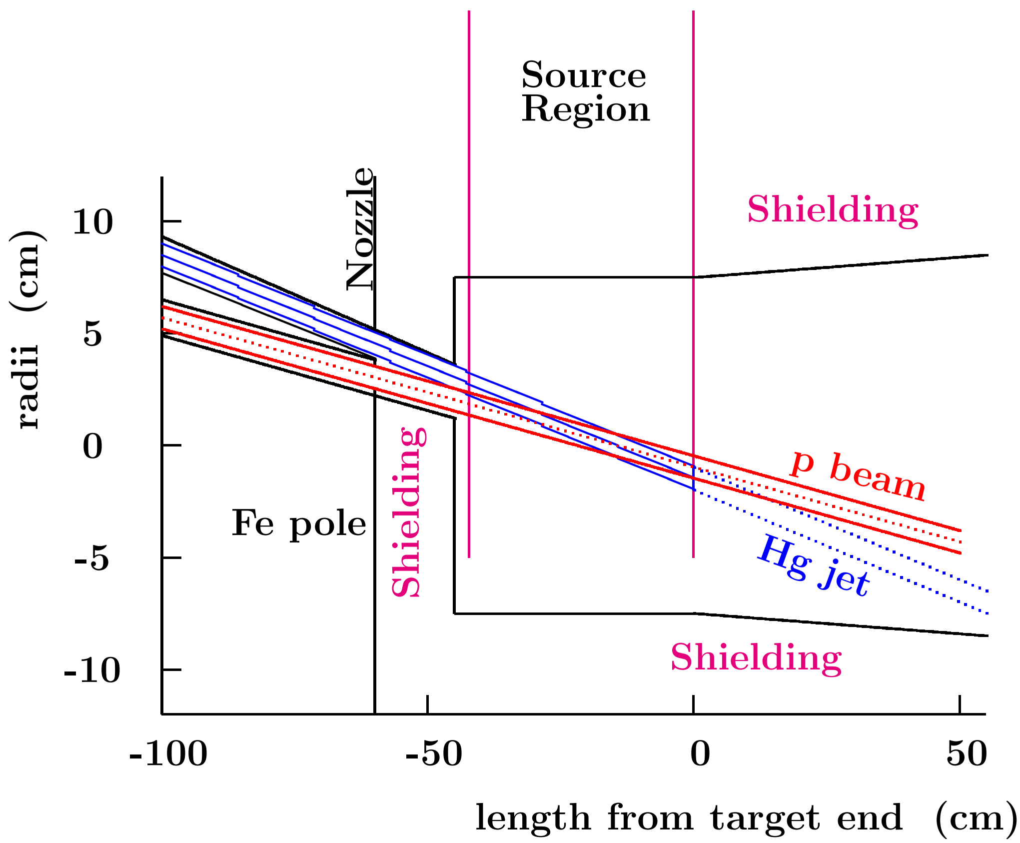




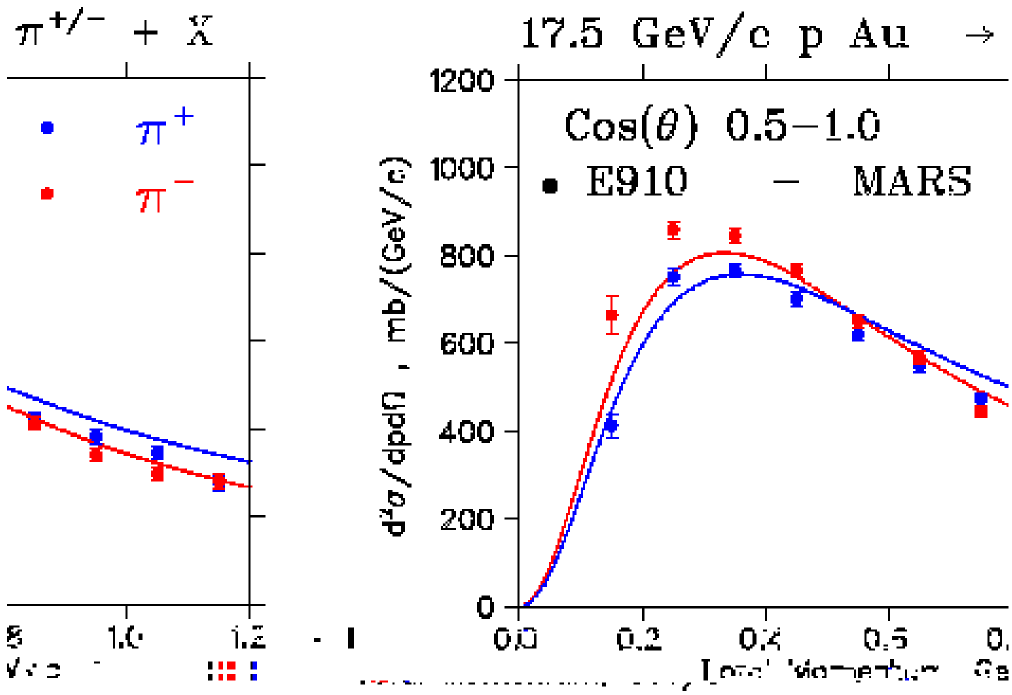
TARGET

Mercury jet Target

- $\approx 2 \times$ Carbon (of study 1)
- 20 m/s replaces disturbed
- Nozzle inside field
- OK to 4 MW ?



Where are the pions ?

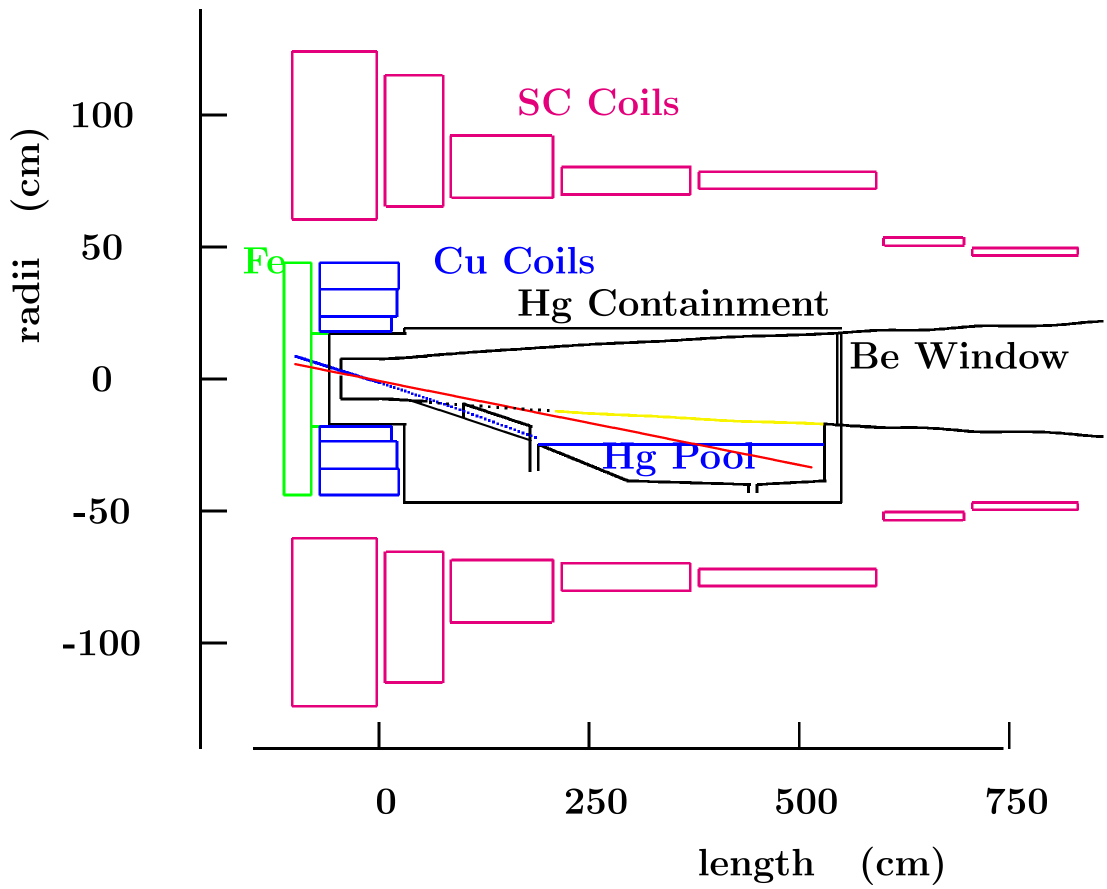


- Peak at low momenta ≈ 300 MeV/c
- $p_{\perp}$ ≈ 200 MeV/c
- Angles large ≈ 45 deg.
- Use 20 T, 8 cm rad, Solenoid
- Captures all below 240 MeV/c
- Slow taper field to 1.25 T
- Pions are folded forward

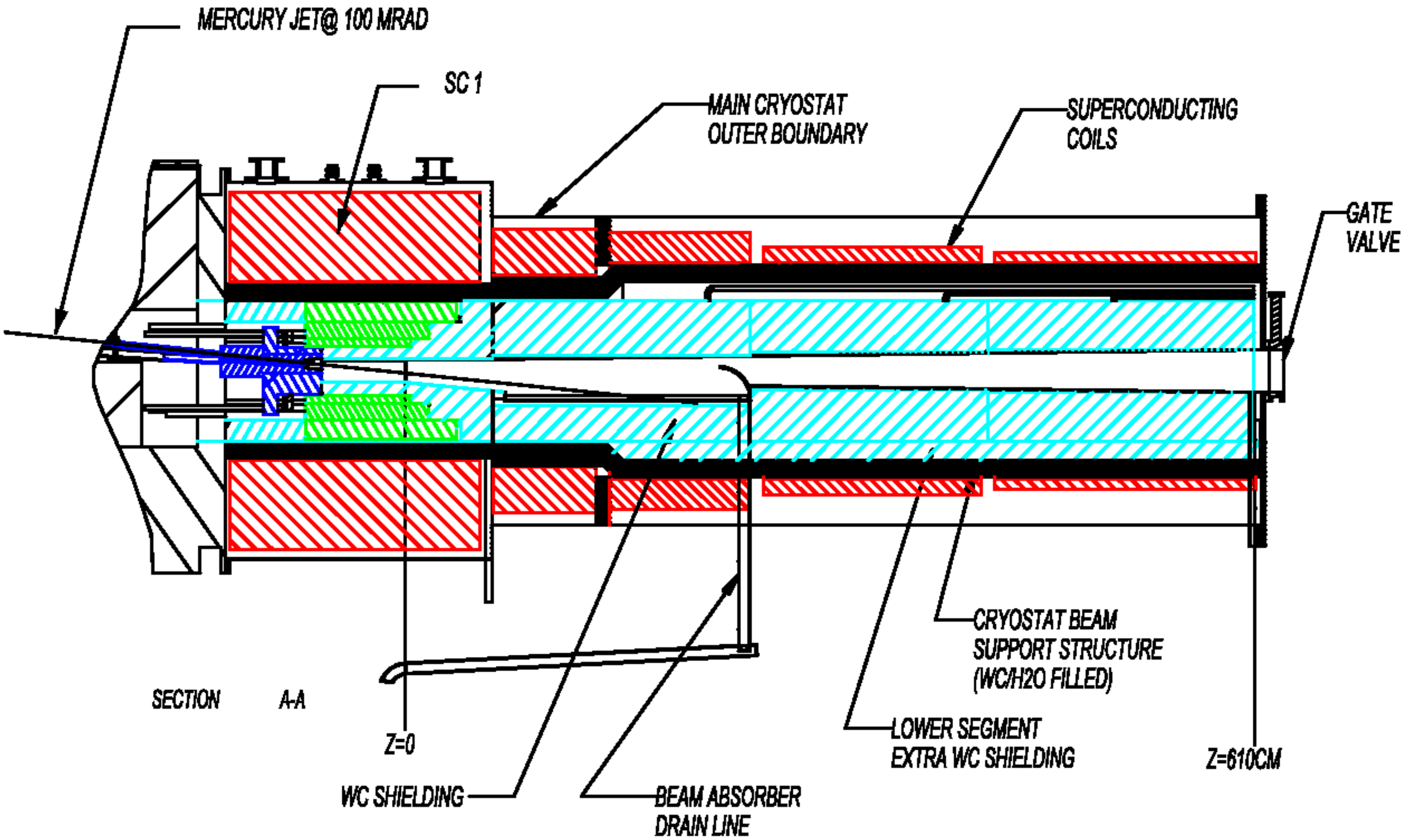
Capture Solenoid & Dump

- 20 T hybrid magnet
  - Hollow Conductor Insert
  - Superconducting Outsert

- Taper field to 1.25 T in 18 m
- Mercury pool Beam Dump



Layout

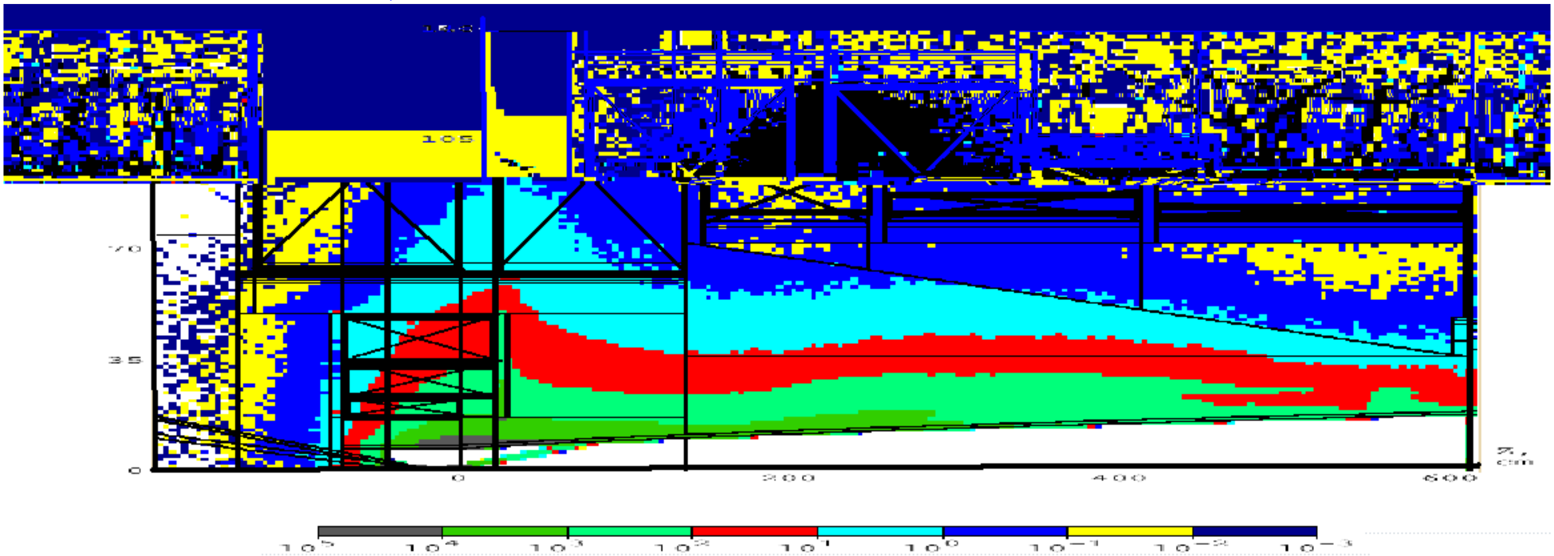


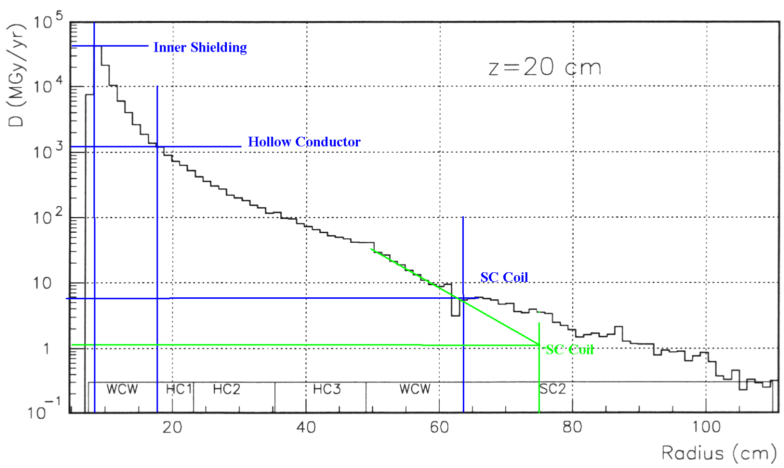
MERCURY JET@ 100 MRAD
SC 1
MAIN CRYOSTAT
OUTER BOUNDARY
SUPERCONDUCTING
COILS
GATE
VALVE
CRYOSTAT BEAM
SUPPORT STRUCTURE
(WC/H2O FILLED)
SECTION A-A
Z=0
LOWER SEGMENT
EXTRA WC SHIELDING
Z=610CM
WC SHIELDING
BEAM ABSORBER
DRAIN LINE

Study 2 Radiation Levels

from Mokhov

for radiation 1 year $\equiv 2\ 10^7$ **s**





Component	radius cm	1 MW Dose/yr Grays	Max Dose Grays	1MW Life years	4 MW life years
Inner Shielding	**7.5**	**5** 10^{10}	10^{12}	**20**	**5**
Hg Containment	**18**	10^9	10^{11}	**100**	**25**
Hollow Conductor	**18**	10^9	10^{11}	**100**	**25**
Superconductor	**65** (75)	**5** (1.2) 10^6	10^8	**20** (80)	**5** (20)

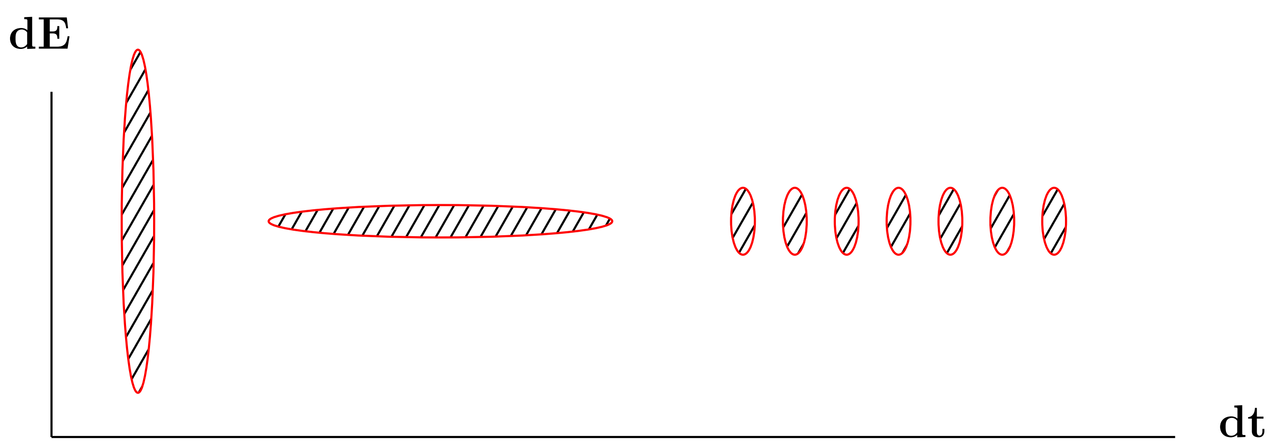
PROBLEM

- Initial pions have rms dp/p $\approx$ 100%
- rms Acceptance of cooling $\approx$ 8%

SOLUTION:

Phase Rotate & Re-Bunch

- Increase dt
- Decrease dE



Simple Phase Rotation

1. **Drift**
2. **Induction Linac to reduce dE/E**
   - **Energy spread non uniform**
   - **dp/p rms ≈ 6%**

e.g. Study 1

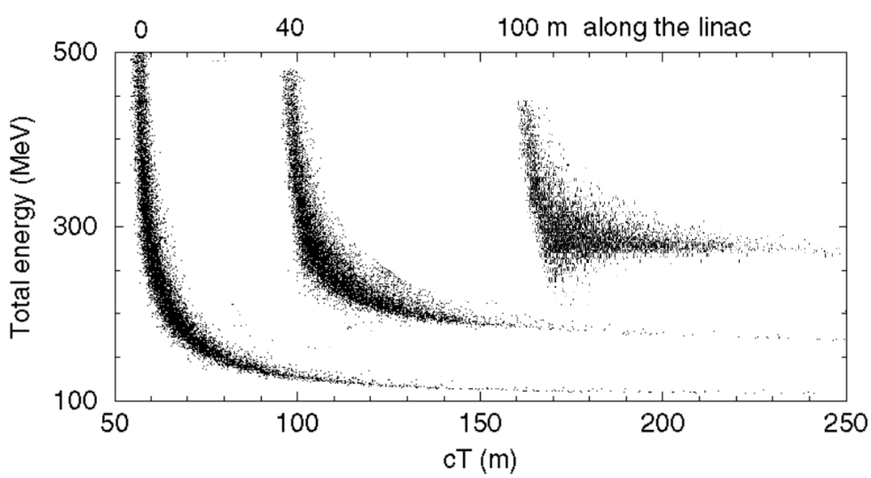


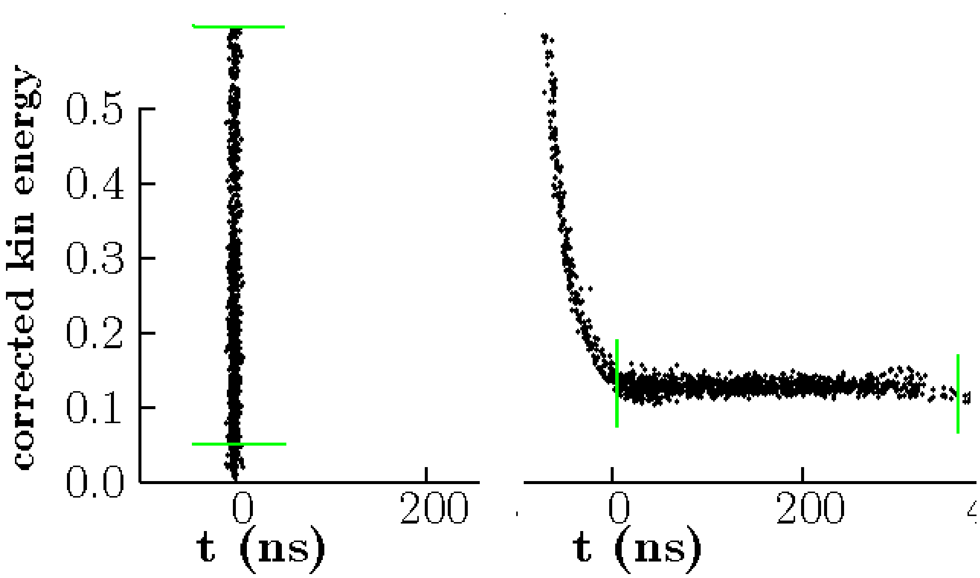
Figure 6: Beam distributions in E-cT phase space along the induction linac. Distributions from L = 0, 20, 60, and 100 m are shown.

3. **Bunch**
   - **dp/p rms ≈ 18%** **too large**

Non-distorting

1. 30 m Drift
2. Induction Linac to modify E vs t
3. Second drift ($\approx$ 100 m)
4. 2nd Induction Linac to reduce dE/E
   - Energy spread more uniform
   - dp/p rms $\approx$ 3%

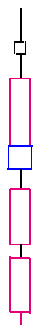
Study 2



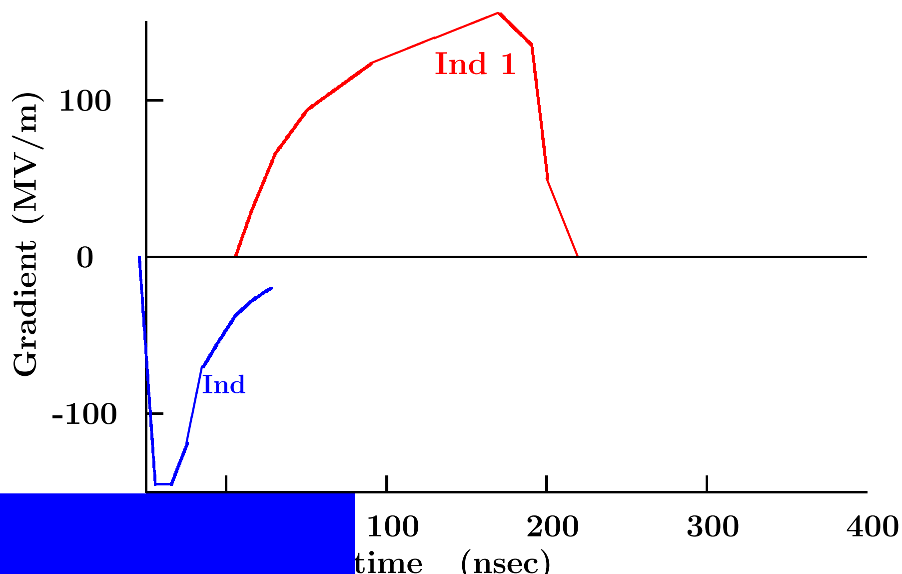
5. Bunch
   - dp/p rms $\approx$ 8% OK

Study 2 Rotation

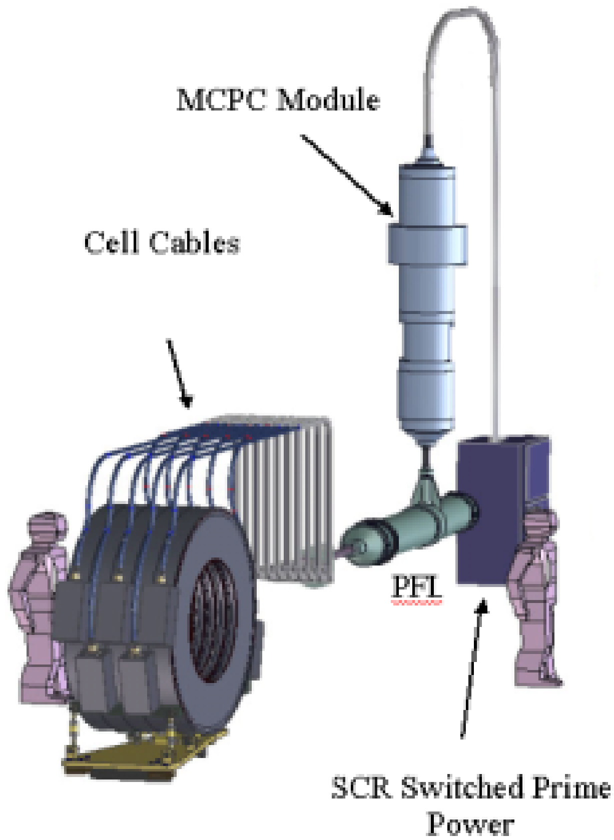
- Non-distorting
- 3 Unipolar Units
- Single pulses (FS1: 4)
- total length 260 m (FS1: 100)



Hg Target	(.45 m)
Induction #1	(100 m)
Mini Cooling	(3.5 m H_2)
Induction #2	(80 m)
Induction #3	(80 m)

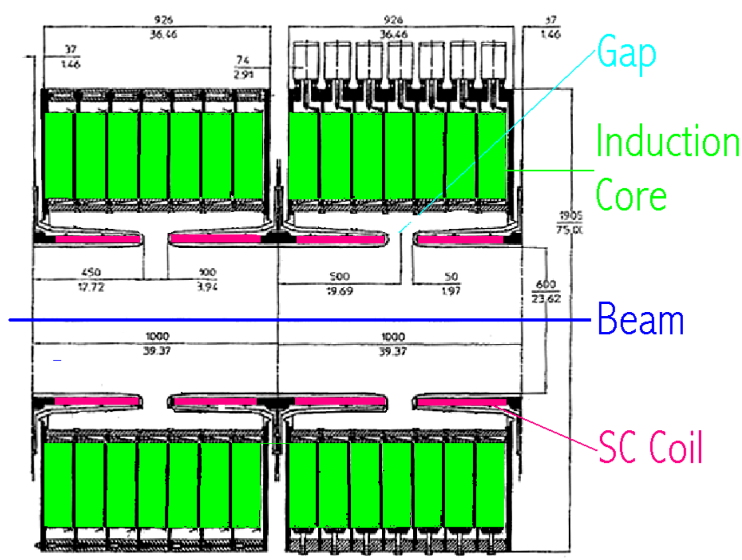


2



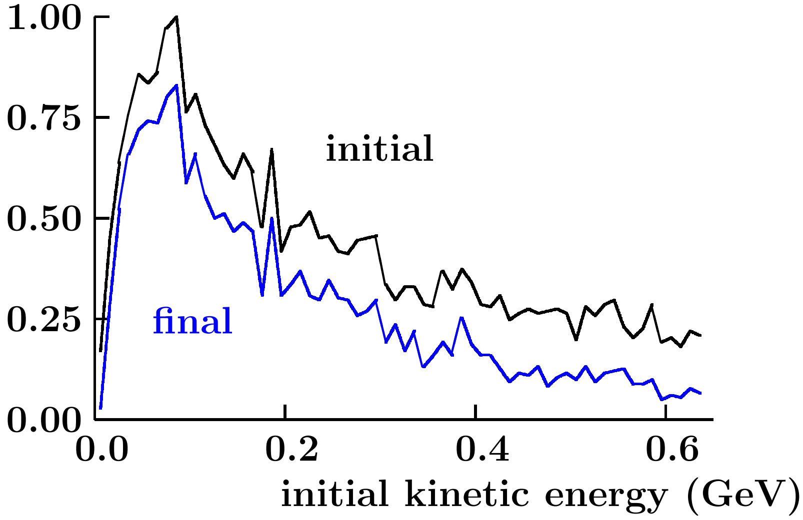
2m Section

95 cm radius similar to ATA or DARHT but Superconducting inside coil



Performance

From target to phase rotation:



RF BUNCHER

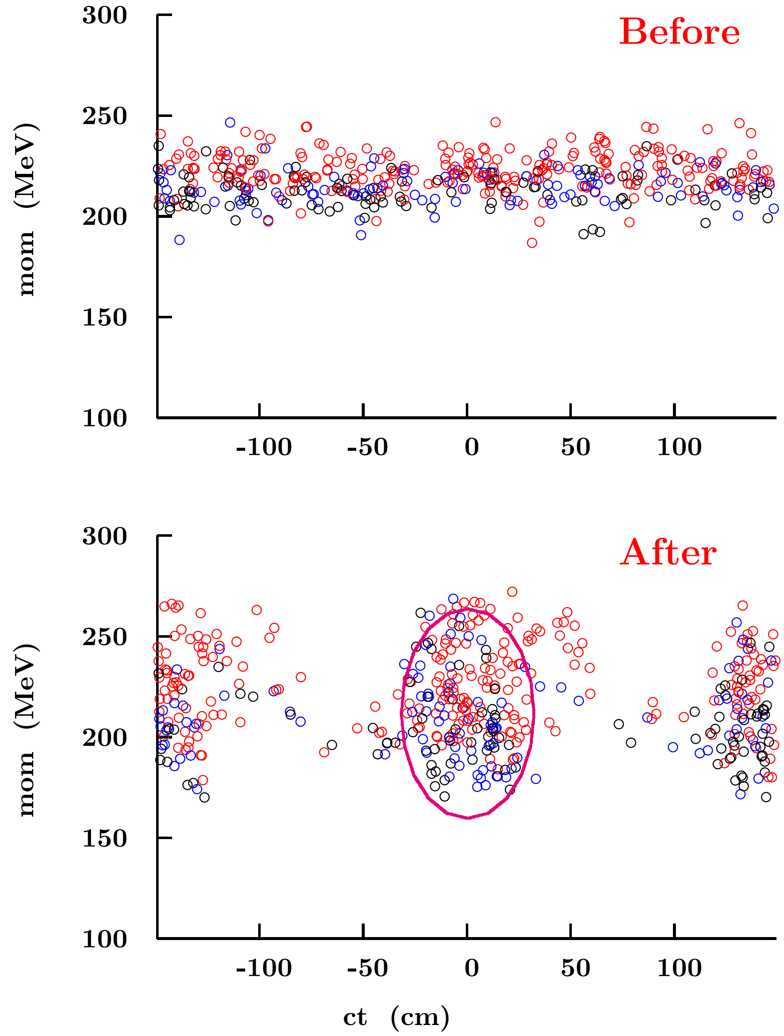
Three stages:

1: Low field 200 MHz rf + 400 MHz harmonic

2. Med. field 200 MHz rf + 400 MHz harmonic

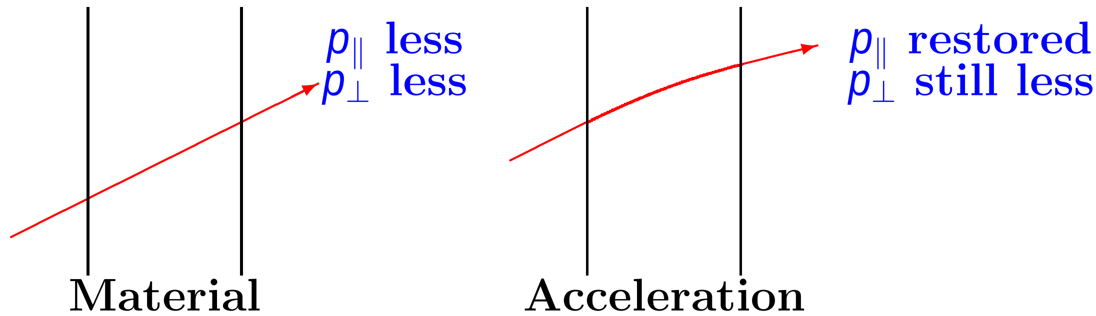
3. Higher field 200 MHz rf

Similar to Study 1

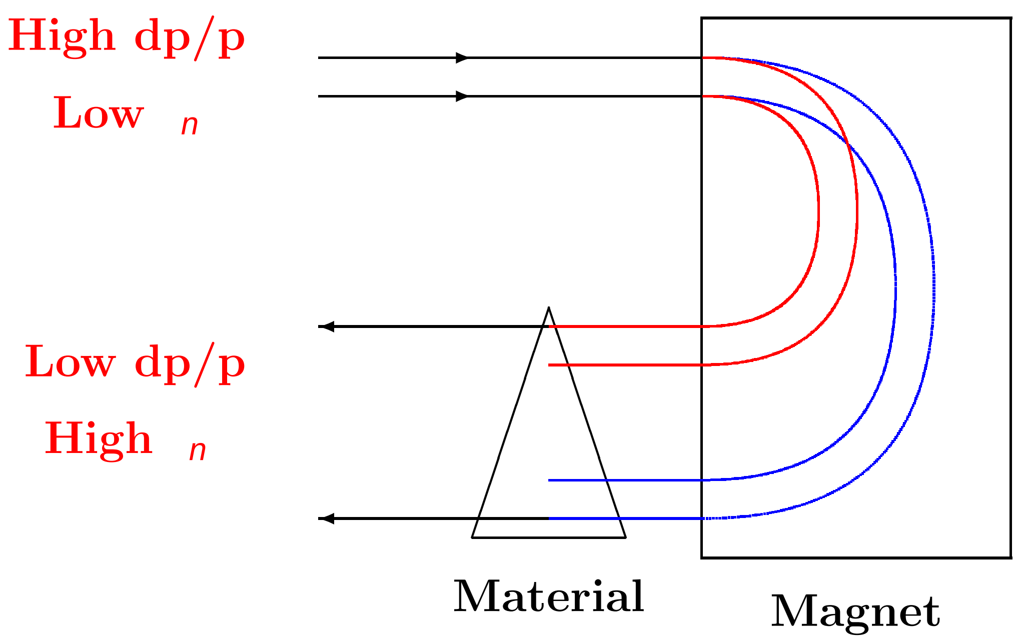


COOLING CONCEPTS

- **TRANSVERSE**



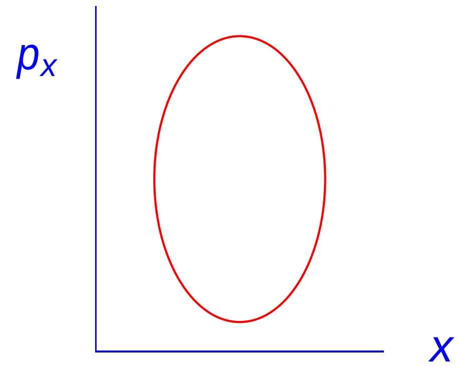
- **LONGITUDINAL EMIT EXCH**



WHAT IS EMITTANCE

$$\text{normalized emittance} \;=\; \frac{\text{PhaseSpaceArea}}{\text{m c}}$$

If x and p_x both Gaussian and uncorrellated, then area is an upright ellipse



$${}_{\perp} = \frac{dp_{\perp}dx}{mc} = \sigma_{\theta}\sigma_{x} \;\; (\gamma\beta_{v}) \qquad\qquad (\pi\ m\ rad)$$

$${}_{\parallel} = \frac{dp_{\parallel}dz}{mc} = dp/p\sigma_{z} \;\; (\gamma\beta_{v}) \qquad\qquad (\pi\ m\ rad)$$

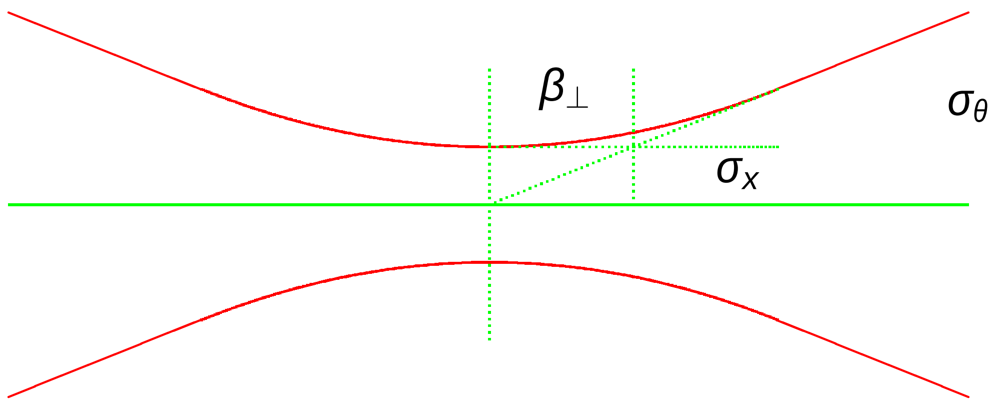
$${}_{6} = {}^{2}_{\perp} \quad {}_{\parallel} \qquad\qquad (\pi\ \ m)^{3}$$

Note that, by convention, the π is not included in the calculated values, but added to the dimension

WHAT IS BETA$_{Courant-Schneider}$

Again upright ellipse, e.g. at Focus:

$$\beta_\perp = \frac{\sigma_x}{\sigma_\theta}$$



Then, using emittance definition:

$$\sigma_x = \sqrt{{}_\perp \, \beta_\perp \, \frac{1}{\beta_v \gamma}}$$

and:

$$\sigma_\theta = \sqrt{\frac{\perp}{\beta_\perp} \, \frac{1}{\beta_v \gamma}}$$

Transverse Cooling

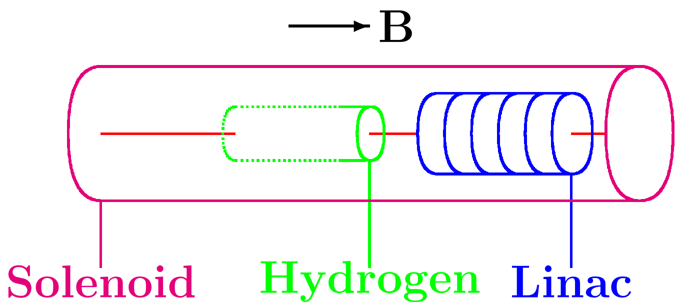
- **Energy Loss lowers** $_{\perp}$
- **Coulomb Scattering Increases** $_{\perp}$
- **Equilibrium:**

$$_{\perp} \propto \beta_{\perp} \frac{1}{\beta_v L_R \; dE/dx} \propto \beta_{\perp}$$

- **Need Low** $\beta_{\perp}$
- **Need Low Z Material**
  - **Hydrogen**
  - **Lithium Hydride**
  - **Lithium**

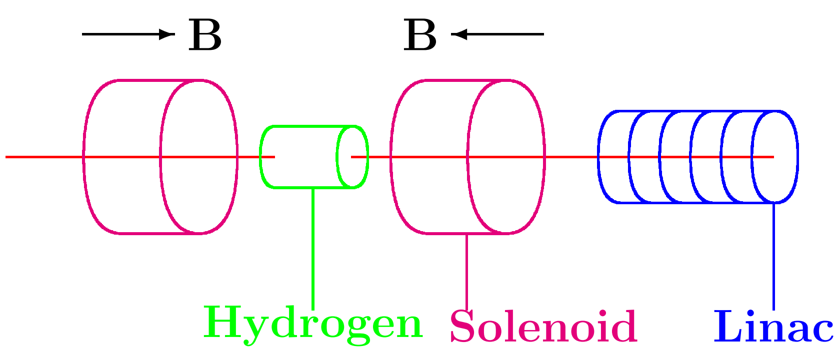
How to get low $\beta_\perp$

SOLENOID



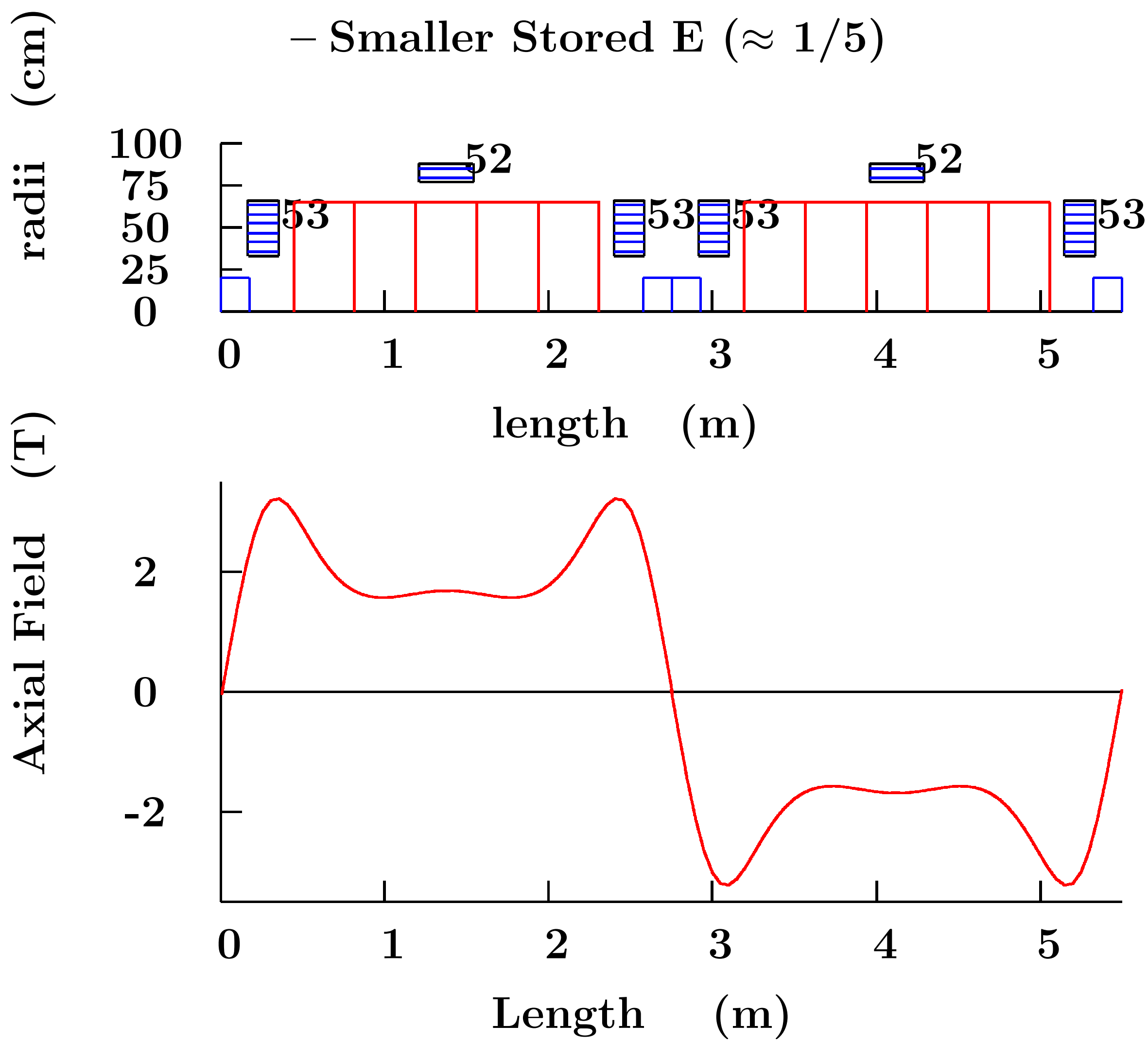
But coils are large, and direction of field must flip at least once, to avoid build up of angular momentum

FOCUS



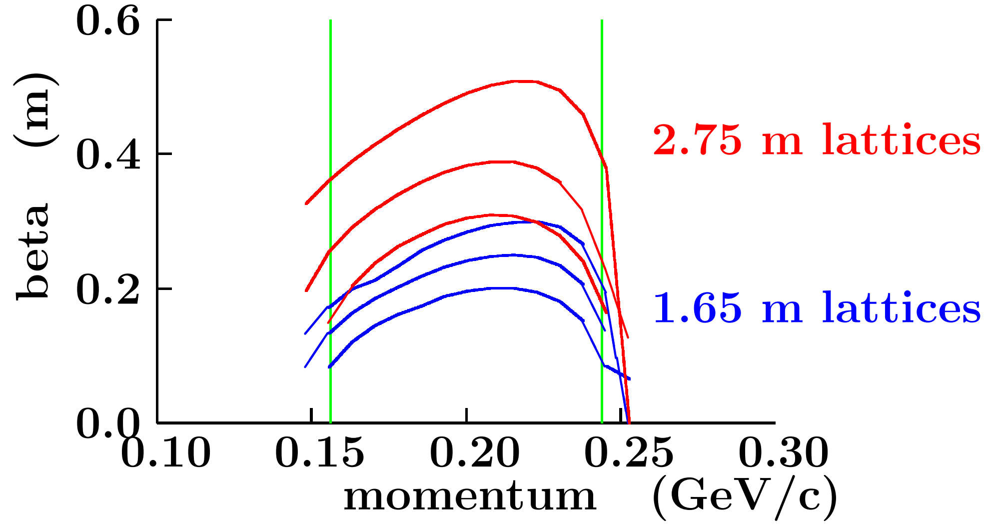
Super FOFO Lattice

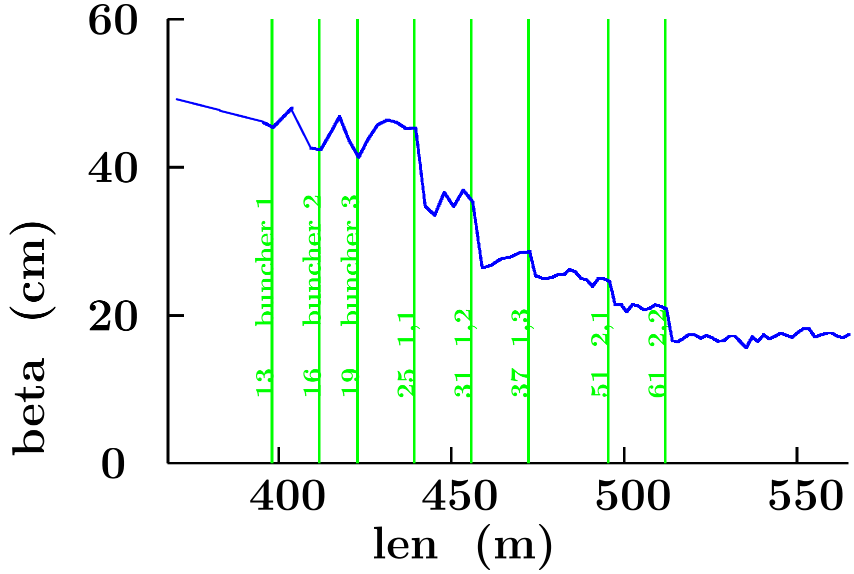
- 110 m long
- 17 MV/m RF
- Super FOFO Lattice
  - Stronger focus
  - Smaller Stored E ($\approx 1/5$)



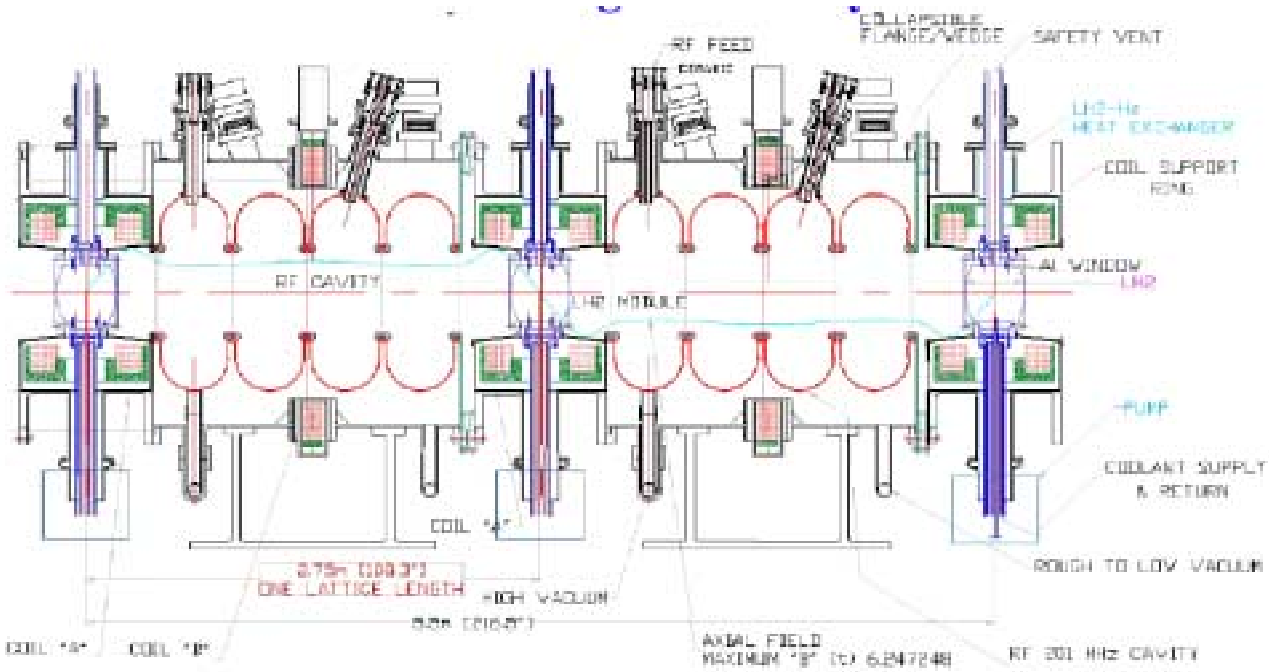
Tapered Lattices

- as emittance falls, lower betas
- maintain constant angular beam size
- maximizes cooling rate

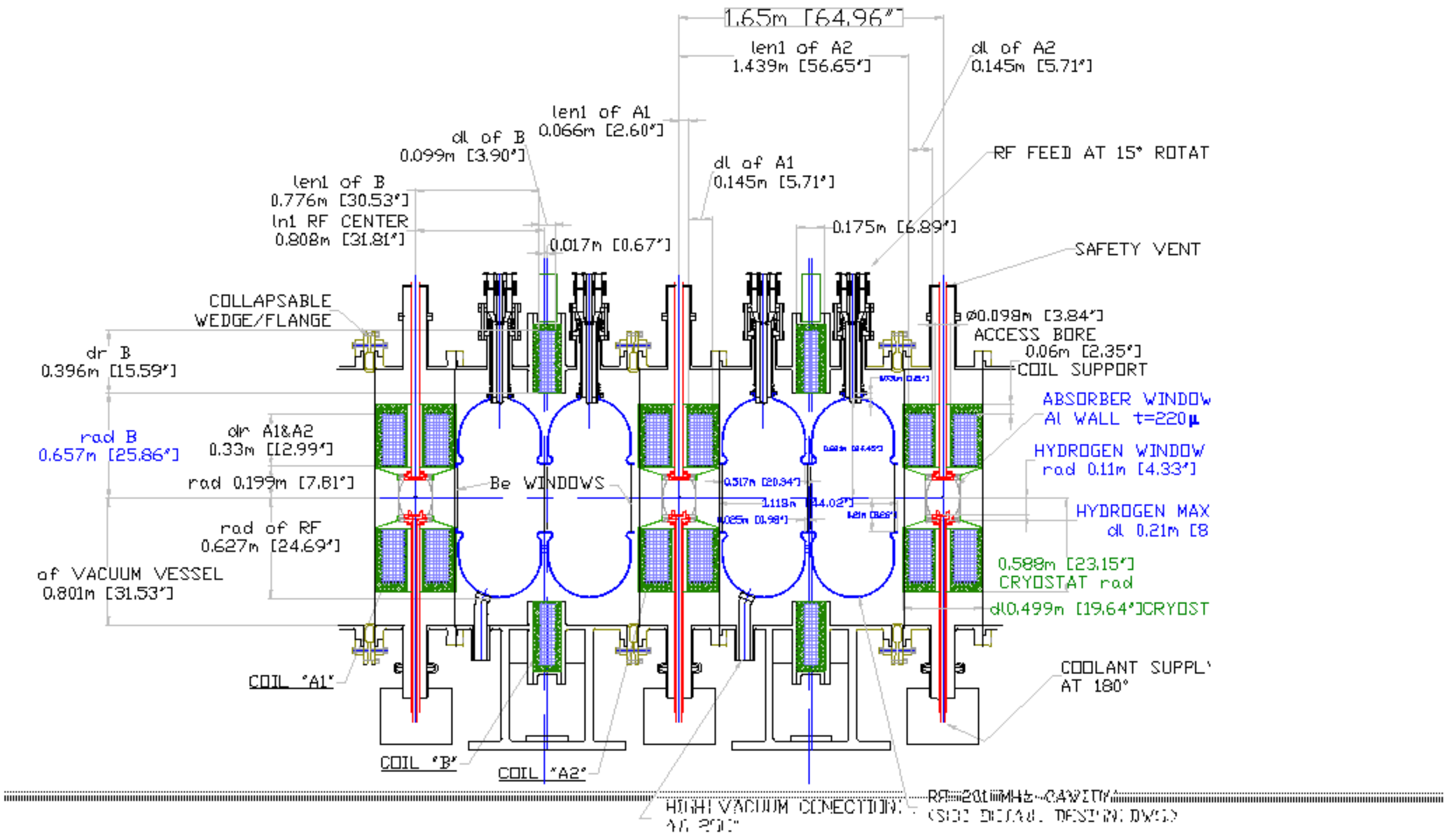




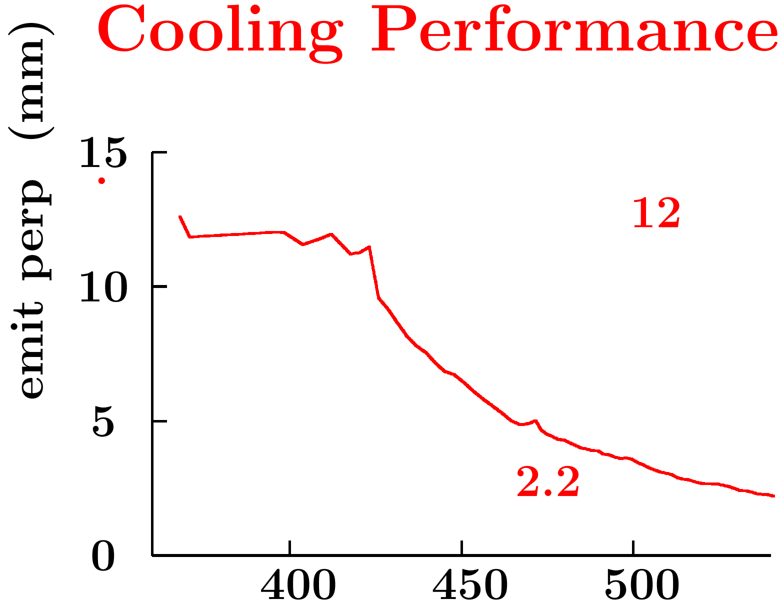
At Start of Cooling

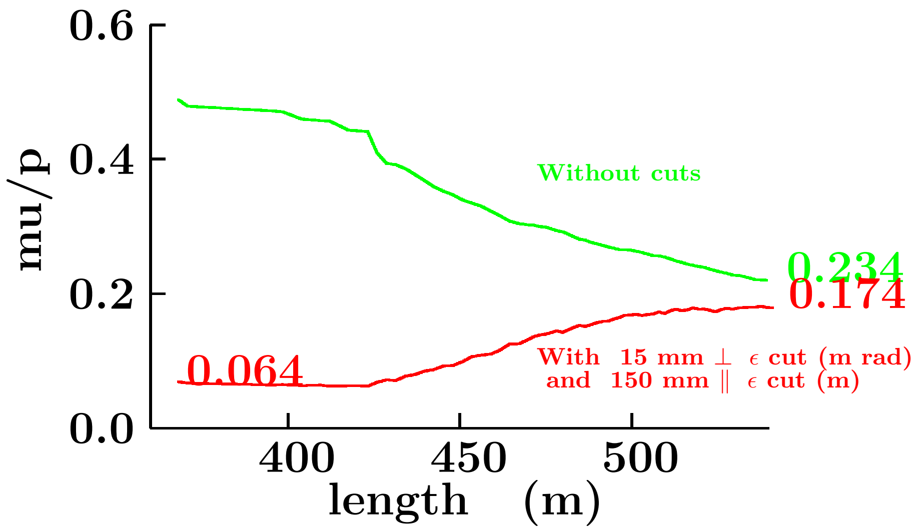


At end of Cooling



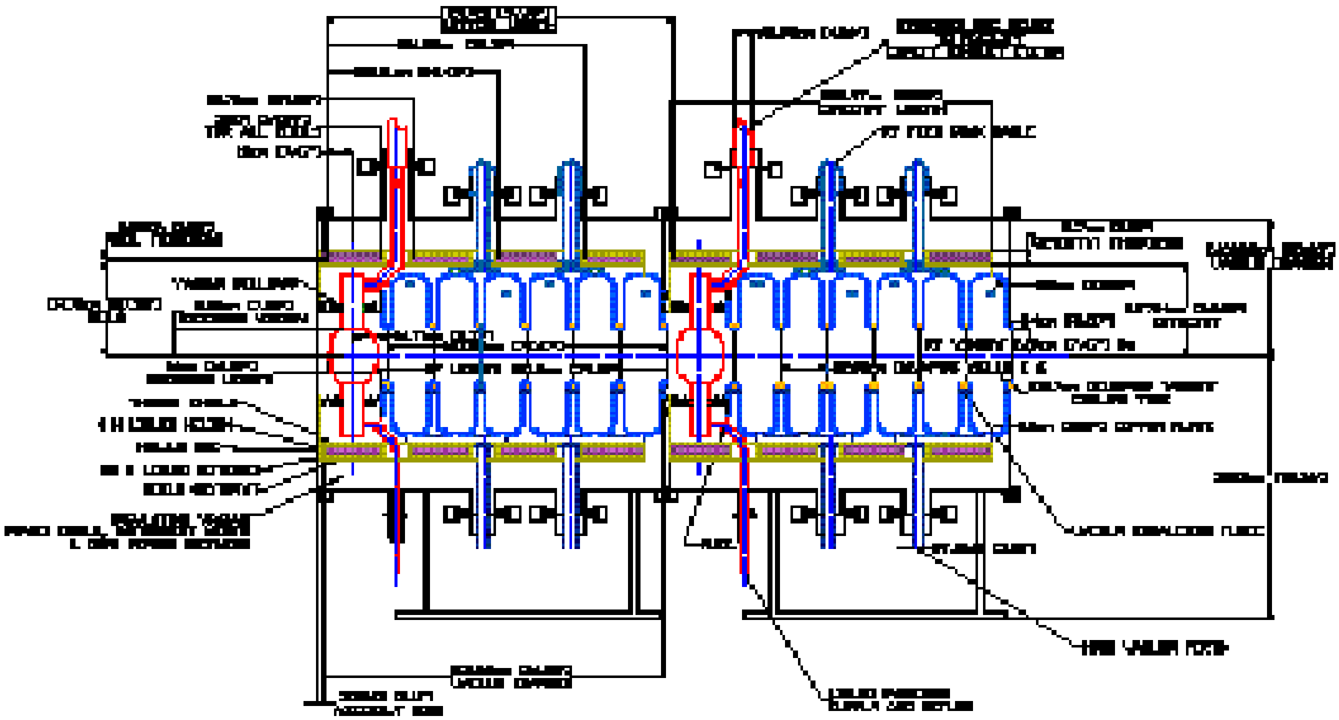
Cooling Performance

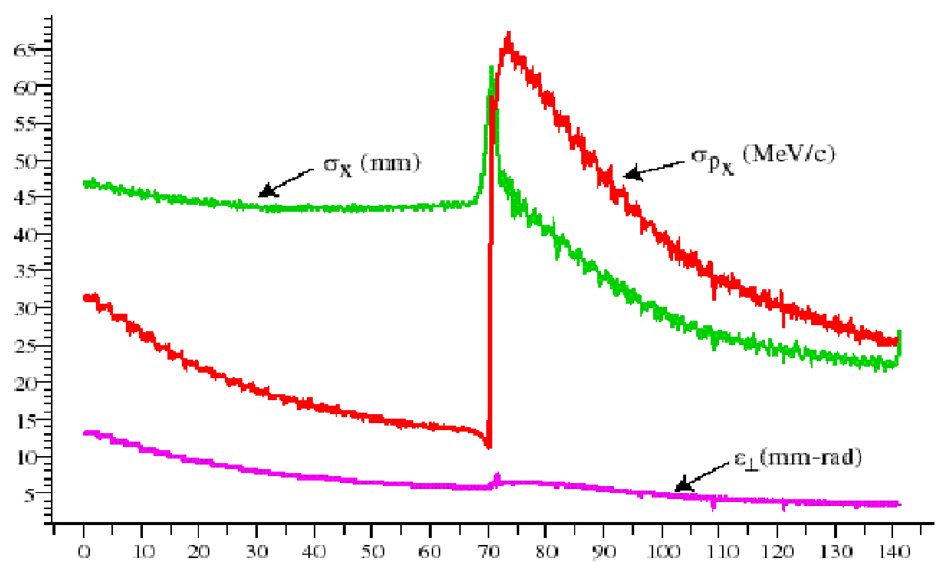




- Gain Factor = 3
- Loss from growth of long emit.
- Avoided if longitudinal cooling

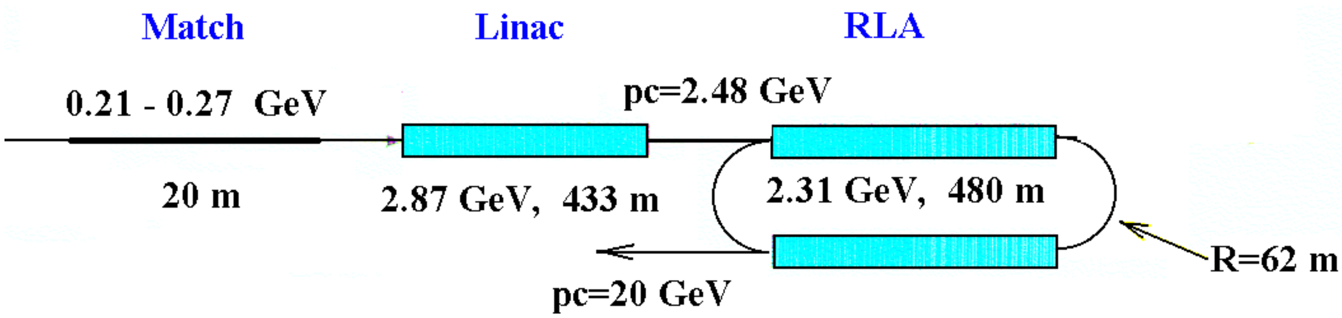
1-2 Flip Alternative



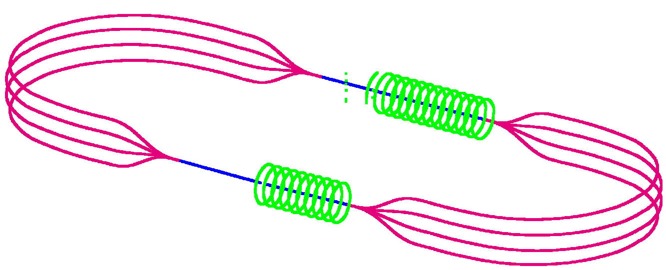


ACCELERATION

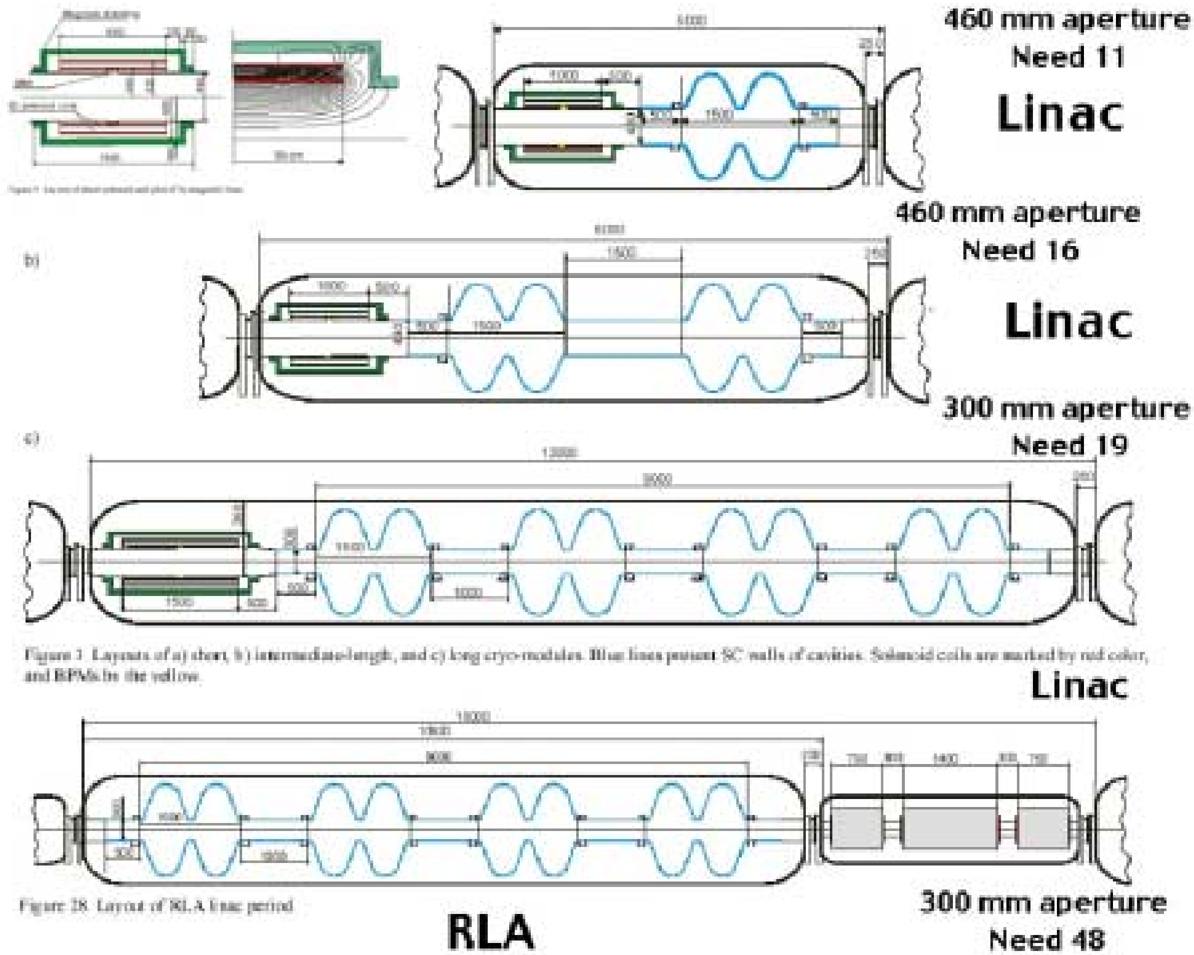
Linac +
Recirculating Linear Accelerator (RLA)



- Superconducting Linacs
- 200 MHz
- Solenoid focus in initial linac
- Quad focus in RLA

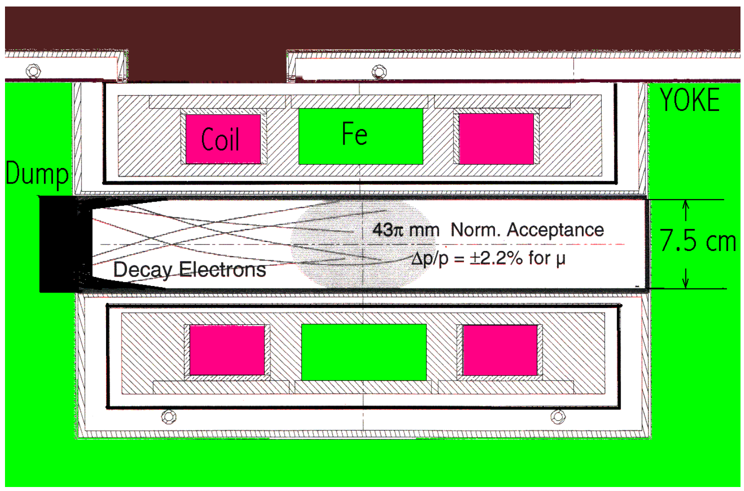


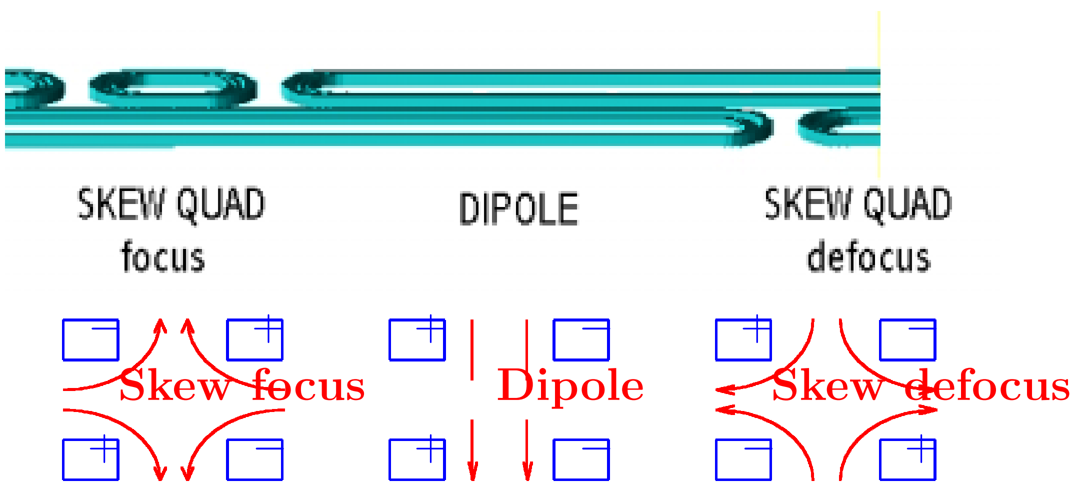
Superconducting Cavities Cornell (200 MHz)



STORAGE RING

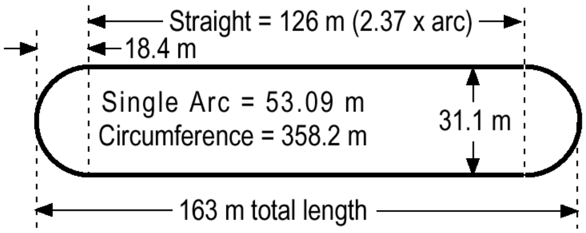
- High Field (to maximize straight/circumference)
- 30 kW (100 W/m) Decay electrons
- Strong focus (large emittance & dp/p)
- Good longitudinal packing factor





Arc Magnet Parameters:

B_1 = 6.93 T, G_1 = 0 T/m, L_1 = 1.89 m
B_2 = 0. T, G_2 = 35.0 T/m, L_2 = 0.76 m
Average B = 4.94 T, L_{cell} = 5.3 m



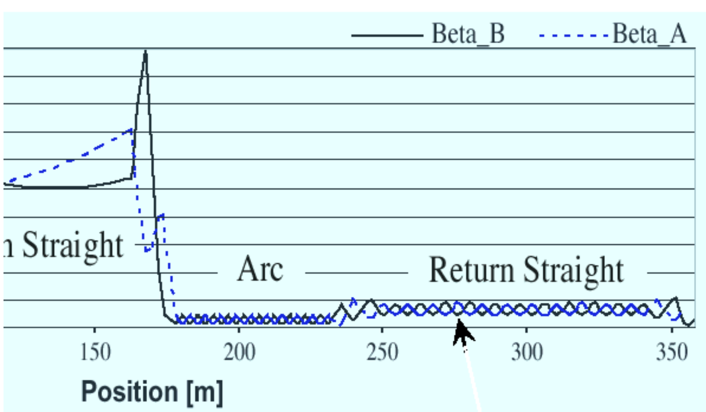
10 Cell Solution
60° Arc Cell Phase
β_{arc} = 8.69 m

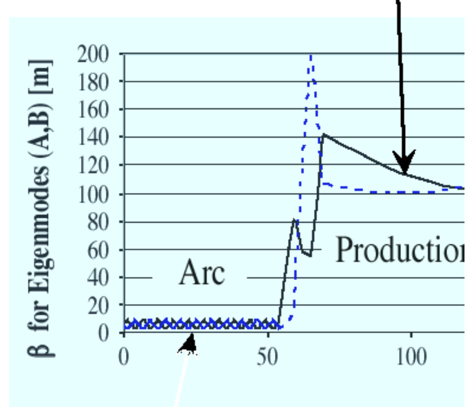
Empty cell has
warm quadrupoles
with G = 27.2 T/m.

$$\text{Geometric Decay Ratio} = \frac{126\text{ m}}{358\text{ m}} = 0.35 \text{ per straight section}$$

ection has increased β for reduced
ses normal conducting quadrupoles.

126 m production straight s
beam angular spread and u



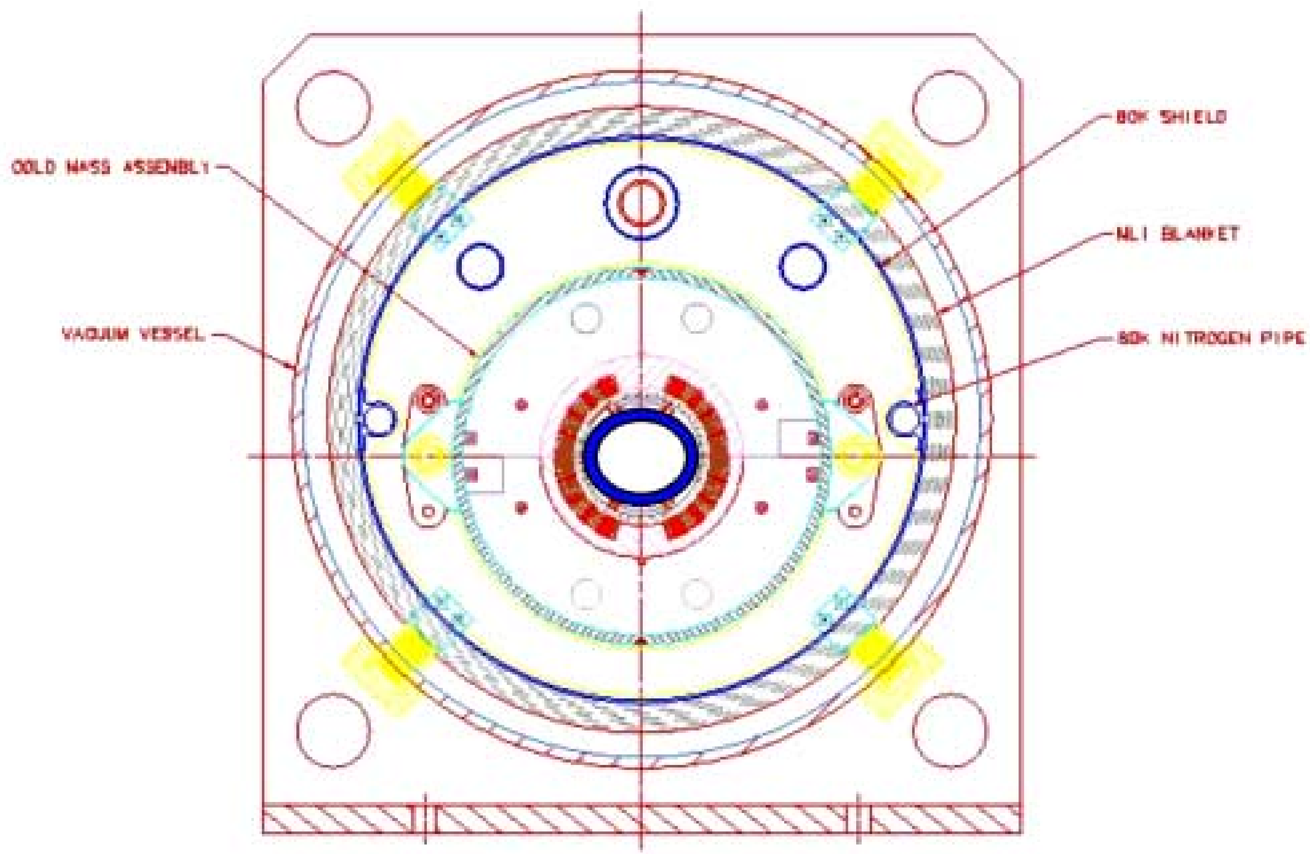


53 m arc is mostly superconducting but has warm sections near each end for collimation.

126 m return straight is used for injection and other machine utility functions. Optics details are TBD.

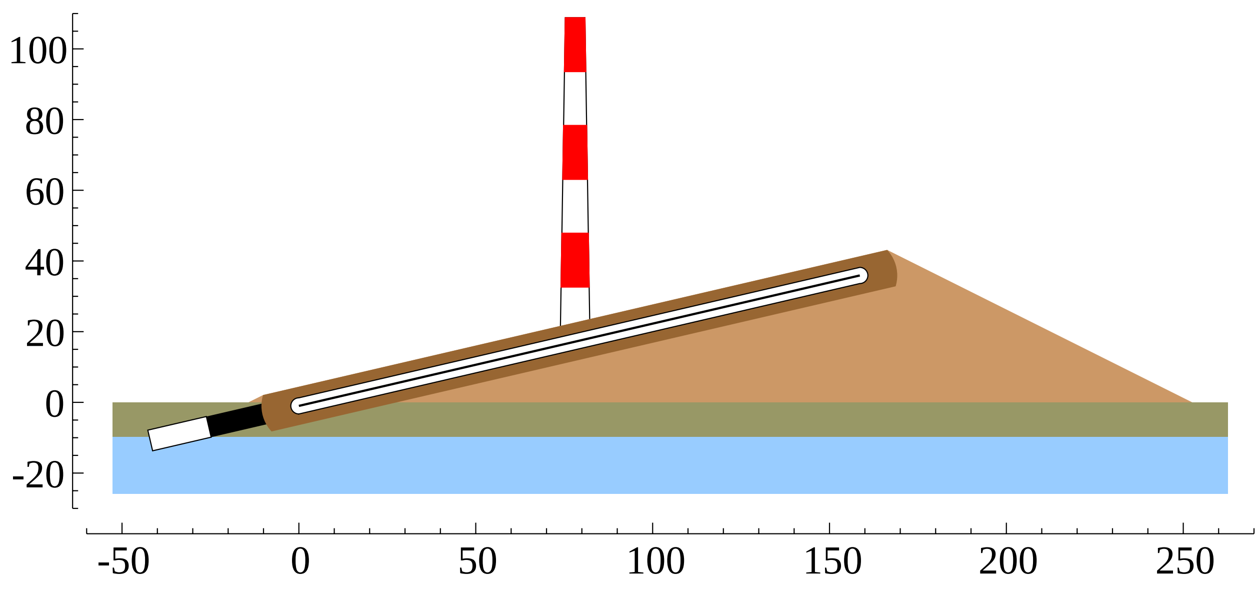
Alternative Conventional Arcs

- **Conventional FODO Lattice**
- **Cosine Theta Magnets**
- **Warm W shield inside**

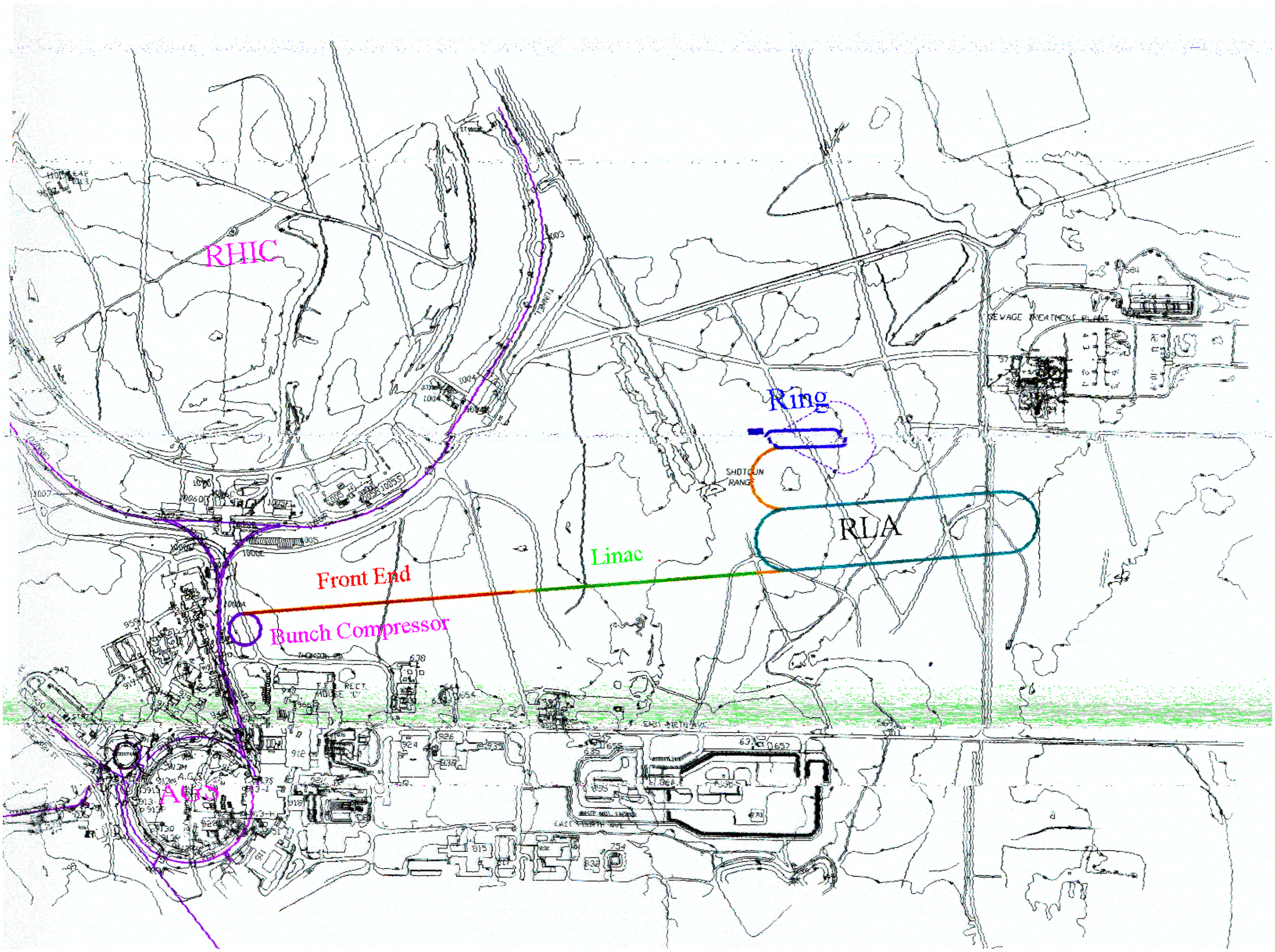


Ring Layout

To Carlsbad	2903	km
Dip angle	13.1	deg
straight	116	m
circ	332	m
decay/circ	35	%
To Homestake	2528	km
Dip angle	11.4	deg
straight	138	m
circ	376	m
decay/circ	37	%
To Soudan	1713	km
Dip angle	7.73	deg
straight	218	m
circ	536	m
decay/circ	40	%



BNL Footprint



FRONT END SIMULATION

Up to and including match to acceleration linac,
(as remembered by Bob Palmer)

- Pion Production & radiation
  - MARS code
  - Checked against 2 other codes
  - Checked against Collaboration AGS Exp E910
  - differences $\approx 20\%$
- Target Geometry
  - Gaussian p beam
  - cylindrical Hg target[1]
  - tilts as specified
- Tracking trough phase rotation and cooling
  - design code: ICOOL
  - tracking in 3D, including spin
  - decays pi-mu, mu-e
  - statistics to 50,000 in, 10,000 out
  - confirmation by DP GEANT
  - tracking differences $\leq 5\%$
  - most error studies by DP GEANT

[1] no distortion or turbulence

- Magnetic Fields
  - Field Maps from coil geometries
    * capture
    * periodic transport
    * field flips in phase rotation
    * Cooling lattice
    * matching between each
- RF Fields
  - Analytic pill-box time dependent[2]
- Materials Interactions
  - dedx: Bethe Block with density effect
  - scatter: Moliere with Rutherford limit[3]
  - straggle: Vavilov + gaussian and Landau limits
- Material geometries
  - H2 with hemispherical ends[4]
  - Al windows with constant thicknesses as specified[5]
  - stepped RF Be windows as specified

[2] noses and rounded outside shape not included, but expected to have negligible effect
[3] some questions remaining on possible overestimate of hard scattering
[4] Study done off line found results insensitive to shape
[5] not tapered

- **Errors**
  - **coil currents**
  - **coil transverse positions**
  - **coil tilts**
  - **H2 densities**
  - **no significant effects with engineering toller-ances and no steering**
- **Overall uncertainty $\approx$ 30%**

FRONT END PERFORMANCE

	p energy GeV	μ/p	μ/p/GeV %/GeV
Study 1	16	0.018	.11
Study 2	24	0.17	.71

Total efficiency gain $\approx 6\ \times$

- No change per MW from 24 vs 16 GeV
- From use of the mercury: 1.9 $\times$
- From phase rotation $\approx 2\ \times$
- From cooling design: $\approx 1.4\ \times$
- From larger acceptance: 1.2 $\times$

IMPROVEMENTS ?

- Longitudinal Cooling(Emittance exchange)
  - Less loss: $\approx 2 \times \mu$/p
  - Cheaper acceleration ?
  - Progress (Thursday)
- Bunch Beam Phase Rotation
  - both signs
  - Reduced Cost
  - Progress (Thursday)
- FFAG Acceleration
  - larger acceptance ?
  - lower cost ?
  - Progress (Thursday)
- Others

CONCLUSIONS

- BNL (like FNAL) is a good site for a ν factory
- Study 2 has $6 \times$ efficiency of study 1
- Upgrade to 4 MW (factor of 4)
- Efficiency gains probable
- Cost reduction probable
- Big step to a Neutrino Factory
- Small step to a Muon Collider